The dependence of low redshift galaxy properties on environment

Simone M. Weinmann, Frank C. van den Bosch, Anna Pasquali

Abstract We review recent results on the dependence of various galaxy properties on environment at low redshift. As environmental indicators, we use group mass, group-centric radius, and the distinction between centrals and satellites; examined galaxy properties include star formation rate, colour, AGN fraction, age, metallicity and concentration. In general, satellite galaxies diverge more markedly from their central counterparts if they reside in more massive haloes. We show that these results are consistent with starvation being the main environmental effect, if one takes into account that satellites that reside in more massive haloes and at smaller halo-centric radii on average have been accreted a longer time ago. Nevertheless, environmental effects are not fully understood yet. In particular, it is puzzling that the impact of environment on a galaxy seems independent of its stellar mass. This may indicate that the stripping of the extended gas reservoir of satellite galaxies predominantly occurs via tidal forces rather than ram-pressure.

1 Introduction

It has long been known that galaxies living in dense regions tend to be redder, less active in their star formation and of earlier type [3, 8, 31]. More recently, large galaxy surveys like the SDSS and reliable stellar mass estimates have indicated that the main parameter governing galaxy properties is however not environment, but stellar mass [20]. It is therefore crucial that environmental effects are studied at fixed stellar mass.

Traditionally, environment has been described in terms of galaxy density (for example out to the n-th nearest neighbour), or in terms of the field versus cluster distinction. Group and cluster finding algorithms applied to the SDSS and other surveys have now made it possible to quantify environment in a way that is physically

S.M. Weinmann
Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands, e-mail: weinmann@strw.leidenuniv.nl

F.C. van den Bosch
Astronomy Department, Yale University, P.O. Box 208101, New Haven, CT 06520-8101, e-mail: frank.vandenbosch@yale.edu

Anna Pasquali
Astronomisches Rechen-Institut, Mönchhofstrasse 12-14, 69120 Heidelberg, Germany, e-mail: pasquali@ari.uni-heidelberg.de

better motivated, expressing it in terms related to the expected underlying dark matter structure [4, 17, 39, 46]. To first order, one can quantify environment simply by discriminating between central and satellite galaxies [36], which acknowledges the fact that those two kinds of galaxies have different average dark matter accretion histories. Finer distinctions between different subpopulation of satellites can then be made according to their host halo mass and group- or cluster-centric distance.

Taking out stellar mass dependencies, and describing environment with a physically better motivated language makes it easier to interpret the observed environmental dependencies. Many different processes have been suggested to drive these environmental dependencies, including ram-pressure stripping of the cold gas [14], removal of the extended (hot) gas reservoir of galaxies by tidal or ram-pressure stripping ('starvation', [23, 3]), harassment by high-speed tidal encounters [27], or a faster mass growth at early times for galaxies that end up in more massive haloes at late times [30]. Much of the recent work on this topic converges towards "starvation" being the main driver of environmental effects [41, 38, 40]. This is an outcome foreseen by early semi-analytical models which included no other environmental effect except the instantaneous removal of the satellite's hot gas reservoir at accretion [19]. However, it has also been shown that this simple recipe likely makes starvation in semi-analytical models overefficient [42, 26], and there are still open questions on how and on which timescales this effect exactly operates.

In this review, we summarize recent results on how various galaxy properties depend on environment at fixed stellar mass. We then outline potential implications of these results on our understanding of galaxy evolution as a function of environments.

2 SDSS group and cluster catalogues

Most of the results described in what follows are based on the Yang et al. [46] group catalogue, which makes use of the SDSS-DR4 [1] and the New York Value-Added Galaxy Catalogue [5]. This group catalogue is constructed using the halo-based group finder of [45], which uses an iterative scheme and priors on the redshift-space structure of dark matter haloes to partition galaxies over groups. Halo masses are estimated from a ranking in total characteristic luminosity or total characteristic stellar mass, with both methods giving very similar results [46]. Details on the galaxy group sample used in most of the studies mentioned below can be found in [35]. Some results come from the cluster catalogue by von der Linden et al. [39], which is based on the SDSS DR4 catalogue and the C4 cluster catalogue [28]. In what follows, a "central" galaxy is defined as the most massive galaxy in its group. All other galaxies which reside in the same group are labelled "satellites".

3 Results

3.1 The dependence of galaxy properties on the satellite-central dichotomy

To first order, we can quantify environmental dependence simply by comparing satellite and central galaxies of the same stellar mass. Several key differences between those two types of galaxies have been found. The most basic difference is that satellite galaxies are redder [35] and have lower specific star formation rates [22] than central galaxies of the same stellar mass. In addition, satellite galaxies are less likely to reveal optical or radio AGN activity, and their AGN activity is weaker than in their central counterparts [32]. In terms of morphology, it is found that satellite galaxies have surface brightness profiles that are, on average, slightly more concentrated than those of central galaxies [35, 43, 16]. As shown by [43], this most likely does not reflect a true difference in the mass distribution, but rather can be explained by fading of the stellar disk due to star formation quenching in the satellites. This is consistent with the finding that satellites and centrals reveal no structural differences if they are matched in both stellar mass and colour [16, 35]. As can be seen in Fig. 1, the fraction of galaxies with a concentration greater than 3 is the same for satellites and centrals at fixed stellar mass. This suggests that the most highly concentrated galaxies (which typically have elliptical morphologies) are not produced by environmental effects.

Fig. 1 The fraction of galaxies with a SDSS concentration greater than 3 for central galaxies (solid line) and satellites (dashed line). Concentration is defined as the ratio between the radius containing 90 percent of the r-band light, divided by the radius containing 50 percent of the r-band light. More details are given in [43].
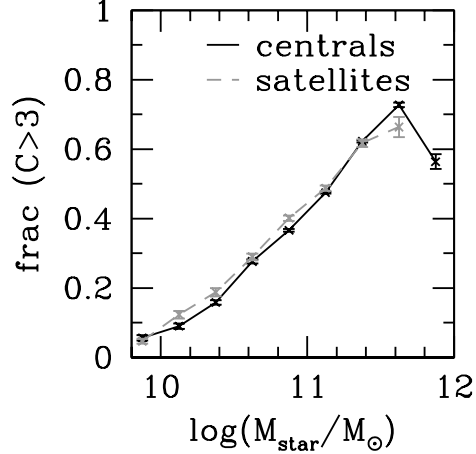
3.2 The dependence of satellite properties on host halo mass

Group catalogues make it possible to study the properties of satellite galaxies as a function of the mass of their host halo. While the average colours of satellites depend only very weakly on host halo mass [36], there seems to be a significant increase of the fraction of red or passive satellites with increasing halo mass [22, 38]. Interestingly, satellites in more massive haloes are older and more metal rich than their counterparts in lower mass haloes [33]. This is shown in Fig. 2, which plots the stellar mass-weighted ages and metallicities of centrals and satellites as a function of host halo mass. The halo mass dependence (and hence the difference between centrals and satellites) is most pronounced at relatively low stellar masses, and disappears at the high mass end [33].

While the older ages of satellites are likely directly related to their larger passive fraction, their higher metallicity is less straightforward to explain. It could indicate that the satellites are the descendants of centrals with higher stellar mass, and thus a higher metallicity, which underwent tidal stripping of their stellar material [33]. However, the amount of stellar mass stripping required is fairly substantial, which is difficult to reconcile with the fact that satellites seem to have the same concentrations like centrals of the same stellar mass (see for example [28]). Another explanation could be that satellites form a significant amount of stars after infall. It is plausible that these would have a higher metallicity than stars formed in a comparable central galaxy due to the lack of new infall of low metallicity ('primordial') gas. However, a significant boost in the stellar mass-weighted metallicity requires that satellites form a relatively large fraction of their stars after accretion, which may proof difficult to reconcile with their high passive fractions. Clearly the origin of the
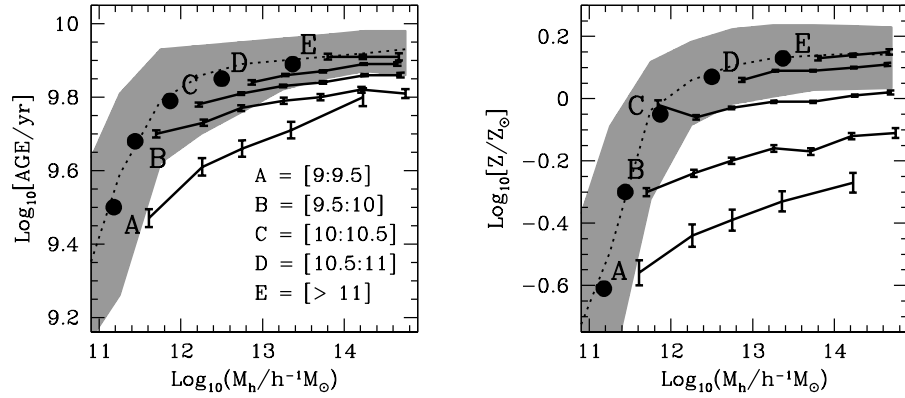

Fig. 2 The mean stellar mass-weighted age (left hand panel) and metallicity (right hand panel) for central galaxies (large filled circles) and for satellite galaxies (lines with errorbars) for different stellar mass bins A-E, as indicated. Results for satellites are shown as a function of halo mass. It can be seen that low mass centrals have lower metallicities than satellites, and that the metallicity for low mass satellites increases with increasing host halo mass. More details are given in [33].

relatively high metallicities in low mass satellites needs to be investigated in more detail, and might give interesting new insights into the processing and recycling of gas in both central and satellite galaxies.

Finally, although there are indications from HOD modelling that there is a relation between the fraction of satellites with AGN activity and host halo mass [29], no such relation has been found using our group catalogue [32].

3.3 The dependence of satellite properties on cluster-centric radius

Dependencies of galaxy properties on group- or cluster-centric distance are most clearly visible in massive clusters where statistics are best and the center of the cluster is easier to define than in poor groups. Fig. 3 shows the fraction of passive satellites in haloes with $M > 10^{14}h^{-1}M_\odot$ as a function of halo-centric radius in the sample used by [44]. Clearly, in these massive haloes the passive fraction of satellites at a given stellar mass increases towards the center [40, 44, 4]. Interestingly, the fraction of galaxies showing signs of *fast recent* truncation of star formation is found to be virtually independent of cluster-centric radius [40], which seems to suggest that *fast* truncation may be unrelated to environmental effects. Finally, the fraction of galaxies hosting a powerful optical AGN has been found to decrease towards the cluster center at fixed stellar mass [40].

Fig. 3 The fraction of passive satellites in clusters with halo masses $M > 10^{14}h^{-1}M_\odot$, obtained from [39], as a function of projected cluster-centric radius. Results are shown for four different stellar mass bins, as indicated [values in brackets refer to $\log(M_{star}/h^{-2}M_\odot)$]. Here 'passive' is defined as having a SSFR $< 10^{-11}$yr^{-1} Note the clear decrease with increasing cluster-centric radius. For more details see [44].
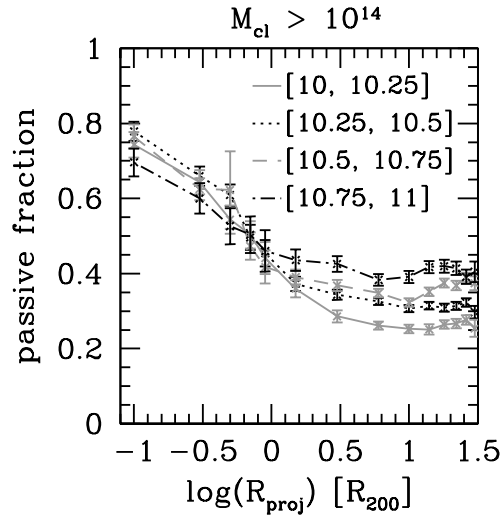
3.4 The puzzling independence of environmental effects on stellar mass

An interesting question that has not received much attention yet is how the impact of environment depends on the stellar mass of the galaxy. Naively, one would expect that stripping of the hot or cold gas in a galaxy by any kind of effect is easier for a shallower potential well, and therefore that low mass galaxies are more vulnerable to environmental effects. To investigate the dependence of the strength of environmental effects on stellar mass, we can introduce a quantity f_{trans}, which gives us an estimate on the fraction of galaxies which were blue at the time of infall and have by now become red due to environmental effects [35]:

$$f_{trans} = \frac{f_{sat,red} - f_{cen,red}}{f_{cen,blue}} \tag{1}$$

with $f_{sat,red}$ and $f_{cen,red}$ the red fraction of satellites and centrals respectively, and $f_{cen,blue}$ the blue fraction of centrals. Note that we assume here that the blue fraction of centrals today corresponds to the blue fraction of the satellites at the time of infall, which should be roughly correct, since most satellites fall in relatively late [35]. As shown in Fig. 4, f_{trans} is remarkably constant at around 40 % from $10^9 M_\odot$ up to $10^{11} M_\odot$. A similar result was obtained by [34]. These findings imply that the probability for a galaxy to become red due to its environment is nearly independent of its stellar mass, which is challenging to understand from a theoretical perspective.

Fig. 4 The transition fraction f_{trans}, which expresses the blue-to-red transition fraction of satellites that were still blue at the time of accretion (see Eq. [1]), as a function of stellar mass. A galaxy is defined as red if $^{0.1}(g-i) > 0.76 + 0.15 \cdot [\log(M_{star}/h^{-1} M_\odot) - 10.0]$. See [35] for details.
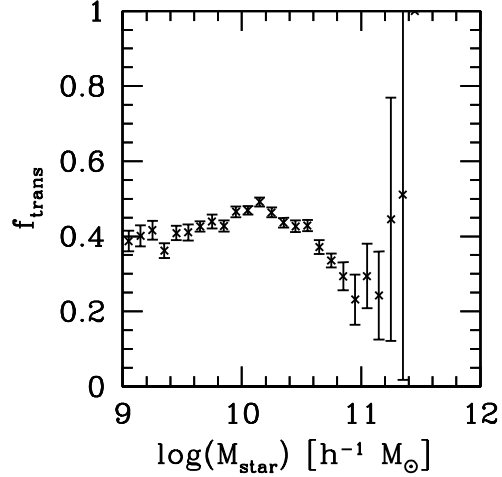
4 Discussion

The fact that satellites and centrals are different is not surprising given that the former are believed to reside in dark matter subhaloes orbiting within a larger dark matter halo (the 'host' halo), while centrals are expected to reside at rest at the center of a host halo. Whereas host haloes continue to grow in mass via accretion, subhaloes lose mass (to their host) due to tidal stripping. This implies that subhaloes, and their associated satellites, also lack the accretion of intergalactic gas associated with halo growth. However, this effect by itself does not necessarily mean that centrals and satellites are different. After all, if satellite galaxies can hang on to their extended haloes of hot gas which they are predicted to have at infall, they may remain 'active' for a relatively long period of time [44]. An additional environmental effect therefore seems required to explain the observed dependencies. Based on all results discussed above, this effect has to have the following properties:

- It is likely to result in a depletion of gas, which directly causes higher passive fractions, lower AGN fractions, and higher average stellar-mass weighted ages in satellites compared to centrals of the same stellar mass.
- It occurs for satellite galaxies in haloes spanning a large range in mass (not only in clusters), but becomes weaker towards less massive haloes, and towards the outskirts of clusters [22, 40, 44, 4].
- It quenches star formation in galaxies on a rather long timescale of the order of 2-3 Gyr [18, 43, 40, 38].
- There are no indications that it results in an accompanying structural transformation [43, 37, 16].
- It is similarly strong for galaxies with different stellar masses [35, 34]

Of all the environmental effects that have been suggested, starvation matches this description best. This effect should take place in all kinds of groups, not only in massive clusters. Its effect on the star formation rate is slow, and it does not lead to any morphological changes in the galaxy. However, how this effect operates in detail is still under debate. Also, it is not a priori clear why it should be similarly strong for galaxies with different stellar masses.

Semi-analytical models that include instantaneous and complete removal of the extended gas reservoir of satellites upon accretion result in a passive or red fraction of satellites that is much too high [42]. It has therefore become clear that starvation has to be a more gradual process, which is taken into account in some of the newest semi-analytical models [10, 44, 15]. However, there are indications that modelling ram-pressure stripping of the hot halo according to standard prescriptions leads to a too high fraction of low mass, passive galaxies [44] and also produces too many satellite galaxies with intermediate colours [3, 44]. This could indicate that starvation (i.e. the depletion of the hot gas reservoir) mainly occurs by tidal stripping, and not by ram-pressure stripping [44]. Another argument for this is that tidal stripping seems to be less strongly stellar mass dependent than ram-pressure stripping [44], which likely helps in reproducing the stellar-mass independence of environmental effects discussed above. It also does not seem entirely unrealistic that ram-pressure

stripping could be overestimated in standard semi-analytical models, as these tend to overestimate the hot gas content of groups [6, 44].

The observation that galaxies in cluster centers and in more massive groups have a higher passive fraction than their counterparts in the outskirts and in less massive groups can have two different implications. Either environmental effects are simply strongest in group centers and in massive clusters, or galaxies residing at smaller halo-centric distances and/or in more massive haloes have on average been satellites for a longer period so that environmental effects have had more time to operate. Indeed, for the semi-analytical model of [7], we find that satellites in more massive systems, and closer to the projected cluster-center, have been satellites for longer period, which is shown in Fig. 5. Neither dependency is surprising. Galaxies that end up in more massive haloes are 'born' in denser environments, and therefore tend to become satellites at earlier times. Also, it takes time for newly infalling galaxies to sink to the cluster center by dynamical friction, which explains the radial dependence (see also [13, 12]). Hence, based on Fig. 5, we conclude that the larger fractions of passive satellites in cluster centers and in massive clusters most likely reflect trends in the time of infall, and do not require that environmental effects are stronger in more massive haloes and/or at smaller halo-centric radii.
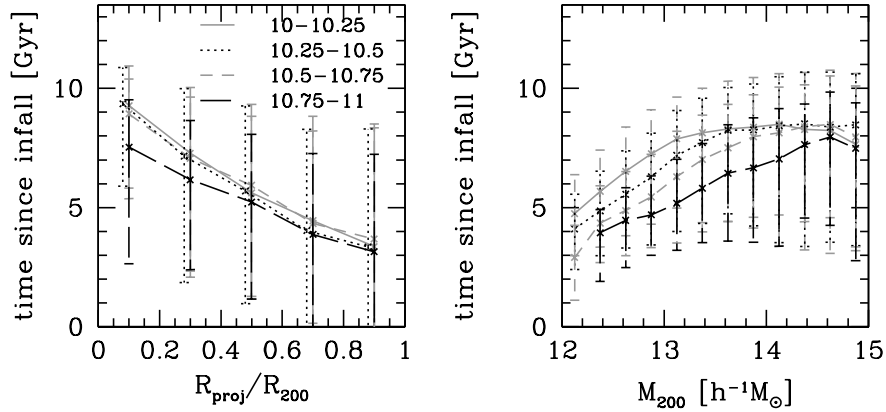

Fig. 5 The median time since galaxies switched from the central to the satellite status for the last time in a semi-analytical model [7], for four different stellar mass bins, as indicated. In the left hand panel, we use a sample of clusters selected in a similar way as in observations, as described in detail in [44], and plot the median time since infall as a function of projected cluster-centric distance. Cluster masses are estimated according to velocity dispersion, as explained in [44]. We only use clusters with "observed" masses of $10^{14} - 10^{15} h^{-1} M_\odot$. In the right hand panel, we plot the median time since infall as a function of group mass, for groups as selected directly in the Millennium simulation. Errorbars in both panels denote the range where 68 % of the measured values lie.

5 Outlook

Models of environmental effects start to be able to reproduce the relations between galaxy properties and environment for low redshift galaxies with masses above $10^9 M_\odot$ [44], indicating that our understanding of environmental effects is improving. Of course, these models should be further tested and refined by using more detailed observational data at low redshift. For example, the gas content of galaxies in different environments can hold important additional clues on the interplay between accretion, SN feedback and environmental effects [21].

Another important test for these models is whether or not they can capture the redshift evolution of environmental dependencies. However, at high redshift there are still several important discrepancies between current semi-analytic model predictions and galaxy properties in general [9, 11, 15] which may need to be addressed first.

Finally, it is important to probe environmental effects at masses lower than discussed here. Although the efficiency of environmental effects seems to be nearly independent of stellar mass in the mass range discussed here, this might well change at even lower stellar masses. To explain the observed population of dwarf elliptical galaxies and their different subclasses as found for example in the Virgo cluster [24], processes additional to starvation, like harassment, or a different formation channel at early times, might be required.

References

1. Adelman-McCarthy J.K. et al., 2006, ApJ, 162, 38
2. Balogh M.L., Morris S.L., Yee H.K.C., Carlberg R.G., Ellingson E., 1997, ApJ, 488, L75
3. Balogh M.L. et al., 2009, MNRAS, 398, 754
4. Bamford S.P. et al., 2009, MNRAS, 393, 1324
5. Blanton M.R. et al., 2005, AJ, 129, 2562
6. Bower R.G., McCarthy I.G., Benson A.J., 2008, MNRAS, 390, 1399
7. De Lucia G., Blaizot J., 2007, MNRAS, 375, 2
8. Dressler A., 1980, ApJ, 236, 351
9. Ferreras I., Lisker T., Pasquali A., Khochfar S., Kaviraj S., 2009, MNRAS, 396, 1573
10. Font A.S., et al., 2008, MNRAS, 389, 1619
11. Fontanot F., De Lucia G., Monaco P., Somerville R.S., Santini P., 2009, MNRAS, 397, 1776
12. Gan J., Kang X., van den Bosch F.C., Hou J., 2010, MNRAS, 408, 2201
13. Gao L., White S.D.M, Jenkins A., Stoehr F., Springel V., 2004, MNRAS, 355, 819
14. Gunn J.E. & Gott J.R.III, 1972, ApJ, 176, 1
15. Guo Q. et al., 2010, MNRAS accepted, arXiv:1006.0106
16. Guo Y. et al., 2009, MNRAS, 398, 1129
17. Hansen S.M., Sheldon E.S., Wechsler R.H., Koester B.P., ApJ, 2009, 699, 1333
18. Kang X., van den Bosch F.C., ApJ, 676, 101

19. Kauffmann G., White S.D.M., Guideroni B., 1993, MNRAS, 264, 201
20. Kauffmann G. et al., 2003, MNRAS, 341, 33
21. Kauffmann G., Cheng L., Heckman T.M., 2010, MNRAS in press, arXiv:1005.1825
22. Kimm T. et al., 2009, MNRAS, 394, 1131
23. Larson R.B., Tinsley B.M., Caldwell C.N., 1980, ApJ, 237, 692
24. Lisker T., Grebel K., Binggeli B., Glatt K., 2007, ApJ, 660, 1186
25. Mastropietro C., Moore B., Mayer L., Debattista V., Piffaretti R., Stadel J., 2006, MNRAS, 364, 607
26. McCarthy I., Frenk C.S., Font A.S., Lacey C.G., Bower R.G., Mitchell N.L., Balogh M.L., Theuns T., 2008, MNRAS, 383, 593
27. Moore B., Katz N., Lake G., Dressler A., Oemler A., 1996, Nat, 376, 613
28. Miller C.J. et al., 2005, AJ, 130, 968
29. Miyaji T., Krumpe M., Coil A.L., Aceves H., 2010, preprint, arXiv:1010.5498
30. Neistein E., Weinmann S.M., Li C., Boylan-Kolchin M., 2010, preprint, arXiv:1011.2492
31. Oemler A., 1974, ApJ, 194, 1
32. Pasquali A., van den Bosch F.C., Mo H.J., Yang X., Somerville R., 2009, MNRAS, 394, 38
33. Pasquali A., Gallazzi A., Fontanot F., van den Bosch F. C., De Lucia G., Mo H. J., Yang X., 2010, MNRAS, 407, 937
34. Peng Y. et al., 2010, ApJ, 721, 193
35. van den Bosch F.C., Aquino D., Yang X., Mo H.J., Pasquali A., McIntosh D.H., Weinmann S.M., Kang X., 2008a, MNRAS, 387, 79
36. van den Bosch F.C., Pasquali A., Yang X., Mo H.J., Weinmann S.M., McIntosh D.H., Aquino D., 2008b, preprint, arXiv:0805.0002
37. van der Wel A., 2008, ApJ, 675, 13
38. van der Wel A., Bell E.F., Holden B.P., Skibba R.A., Rix H.-W., 2010, ApJ, 714, 1779
39. von der Linden A., Best P.N., Kauffmann G., White S.D.M., 2007, MNRAS, 379, 894
40. von der Linden A., Wild V., Kauffmann G., White S.D.M., Weinmann S.M., 2010, MNRAS, 404, 1231
41. Weinmann S.M., van den Bosch F.C., Yang X., Mo H.J., 2006a, MNRAS, 366, 2
42. Weinmann S.M., van den Bosch F.C., Yang X., Mo H.J., Croton D.J., Moore B. 2006b, MNRAS, 372, 1161
43. Weinmann S.M., Kauffmann G., van den Bosch F.C., Pasquali A., McIntosh D.H., Mo H., Yang X., Guo Y., 2009, MNRAS, 394, 1213
44. Weinmann S.M., Kauffmann G., von der Linden A., De Lucia G., 2010, MNRAS, 406, 2249
45. Yang X., Mo H.J., van den Bosch F.C., JIng Y.P., 2005, MNRAS, 356, 1293
46. Yang X., Mo H.J., van den Bosch F.C., Pasquali A., Li C., Barden M., 2007, ApJ, 671, 153